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Space Orbiter Engineering Change Control in Context of Systems Engineering

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ABSTRACT

In this research, an engineered process with a new approach to change control is presented and implemented on a complex space product. This approach involves using design constraint levels in a combination of two design structure matrix (DSM) structures and a systematic process for controlling changes. The system process includes the use of the system change evaluation code, how to create the transfer model, and the management evaluation of the requested change. While using similar existing methods in the literature, this paper provides a systematic approach to apply the knowledge of the designers of a space project to guide change control of large engineering projects, including managerial change control decisions and how to identify the best path for the change control process. Finally, a space orbiter has been selected for a brief implementation of a case study. The comparative results show the benefit of the proposed approach.

Keywords

Change control, Change evaluation code, Trade-off study, Transfer model, Design matrix.

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1. Introduction

Engineering change is a major and significant activity in industrial projects. Engineering changes exist from the explanation of concepts to the design and implementation process, construction and operation, and even after-sales service (Tang et al., 2008). The different phases of the life cycle of an aerospace product are described in (Kapurch,2010). However, all the art and science of systems engineering should be applied in the design phases because changes in subsequent phases cost up to 100 times more. Also, about 90% of the product life cycle cost is affected by the variant finalized at the end of the preliminary design phase (Anderson, 2014). On the other hand, various researches state that "design changes" constitute one-third of engineering design capacity (Kanike and Ahmed, 2007; Fricke et al., 2000; Maier and Langer, 2011). Comprehensive product management is the key to success in business management, and change management is at the core of comprehensive product management. An engineering product consists of many components, subsystems, and the relationships between them, and making a change in a component or subsystem creates a chain of changes in the product. However, the usual situation of product design and production shows that the core of engineering changes is mainly focused on tracking and storing engineering changes. There is a lack of quantitative analysis and evaluation of these changes (Tang et al., 2010). Among product design activities are "engineering changes" that can significantly propagate and impact product development (Li et al., 2012).

In this article, requirements are related to many components, and each of these components can be an Originating change Component (OCC) in a way that meets their requirements or changes. An initiating component of change is related to several " Change Propagation Path (CPP)" (Tang et al., 2016). This article develops how to search for optimal change propagation paths for " Change Requirement ". A review of articles from 1981 to the present in Table (1) lists the major articles that have used the above methods to control change.

As can be seen, the "matrix-base" method has the most use, and the "model-base" method has the least use in engineering change management. The theoretical model is not always achievable or not always complete, and therefore it is necessary to extract some kind of dependency model (Hamraz et al.; 2012). This model is much simpler than a theoretical model that focuses on specific aspects of the product or system. This model does not require precise equations and logical rules between parameters but simultaneously allows us to achieve 1-direction of the changes and 2- predict new values.

Table 1. Comparison of different methods in control of engineering changes (Masmoudi et al., 2017)

Row	Paper Name	Change Characterization			Resolution method			Propagation Visualization		
		Likelihood	Qualitative Impact	Quantitative Impact	Matrix -based	Model -based	Algorithm -based	Propagation Tree	Propagation network	Change Propagation Index(CPI)
1	Cheng and Chu (2012)			*	*				*	*
2	Chua and Hossain (2011)		*		*	*				
3	Clarkson et al., (2004)	*		*	*		*	*		
4	Cohen et al., (2000)		*		*	*	*		*	
5	Flanagan et al. (2003)		*		*				*	
6	Giffin et al., (2009)	*			*			*	*	*
7	Hamraz et al. (2012)	*		*	*		*	*		
8	Hamraz et al. (2013)	*		*	*	*				
9	Keller et al., (2005)	*		*	*			*	*	
10	Kim et al., (2013)	*		*	*			*	*	*
11	Kusiak and Wang (1995)		*	*			*		*	
12	Li and Zhao (2014)	*		*		*			*	
13	Li et al., (2016)	*		*		*			*	
14	Oduncuoglu and Thomson (2011)	*			*	*				
15	Rutka et al., (2006)	*	*		*			*		
16	Steward (1981)				*					
17	Yang and Duan (2012)			*					*	*
Total papers		10	5	10	13	6	4	6	15	4
Present Paper		*	*	*	*	*	*			*

In the pure model-based method, existing models are used to specify new values as well as the direction of the changes. While in the pure dependency model, it is not possible to determine new definite values, but by searching for the direction of change, these values can be predicted, and the end path of propagation of changes can be determined and predicted (Masmoudi et al., 2017). In this paper, with the help of methods and techniques, the effective phases of design are given serious attention. This is one of the differences between this research and similar ones.

As seen in Table (1), in addition to the various techniques developed in the study of engineering variations, structural design matrixes have been widely welcomed to maintain the relationship between the parameters. DSM is a good tool for mapping information flow and storing its effects on the product (Tang et al., 2008). The strengths of this study compared to similar studies are examined:

1- In most of the work done, less control and management of engineering changes is in the important design phases, while the current research focuses on the design phase.

2- Combining product and activity[1] matrixes and creating matrixes CA-DSM[2] that create sensitivity matrixes by combining activities and product elements. These matrices help the chief designer predict propagation changes.

3- A combined work of most methods listed in Table (1) has been done.

4- Relying on the knowledge of the chief designer in parallel with the change control software in controlling the propagation of change and achieving the most optimal path of change.

5- Implementation flexibility in engineering projects.

6- Defining several indicators to quantify the control of change propagation and choosing the most optimal path of change in the areas of the probability of effect, resources used, time, improvement of requirements, and bottlenecks.

7- Emphasis on the role of "Configuration Management Center[3]" as a command center for change control in an industrial environment.

2. Problem statement

Engineering Change Management (ECM) is a significant activity in product design and development (Kanike and Ahmed, 2007). This paper presents change management planning for complex systems such as aerospace products. The operation in many papers is not a suitable solution for complex systems and can only be implemented for products with low interactions. Difference control changes in complex systems such as aerospace products are summarized as follows:

- Very high diversity of system parameters
- Extensive interactions between different components

[1] Activities are derived from design process
[2] Components Activity- Design Structure Matrix
[3] CMC

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- Extensive knowledge of the relationship between components
- Interrelated parameters with each other
- Many limitations of design and manufacturing

The above items complicate the process of predicting change control. If we control the changes according to the usual models, we will deal with a large chain of changes without an endpoint. Therefore, the function of this activity can be summarized in the following cases:

- Development of conceptual design (propagation of design changes)
- Product life cycle controllability
- Management control of changes in design processes
- Tangible relationship between all sub-sectors involved in project activities
- Change control in products with high and complex interactions

3. Problem-solving methodology

In this paper, the structure of change control planning for complex systems consists of six parts:

- CA-DSM matrix (interactions between parameters)
- Levels of parameter constraining in the design process
- Engineering change evaluation code (estimating the number of interactions between CA-DSM matrix parameters and identifying the sensitivity range of all parameters)
- Transfer model between parameters
- Measuring change from the perspective of the configuration management center
- A comprehensive change control algorithm

The logic of this research is also shown in figure 1. In column one, design, technical management, and optimization are observed without using systems thinking. In the second column, the proposed systems thinking tools are included, and in the third column, the new and modern combination of the traditional method and systems thinking can be seen. In the fourth column, the selected technique (from the set of techniques of the third column), which is used in this article, is also mentioned.

For example, in the second row, traditional design without technical management plus systems thinking leads to systems engineering. We have used the change management process from among the various processes and tools of systems engineering, which finally combines the three selected techniques for MSDO Change control.

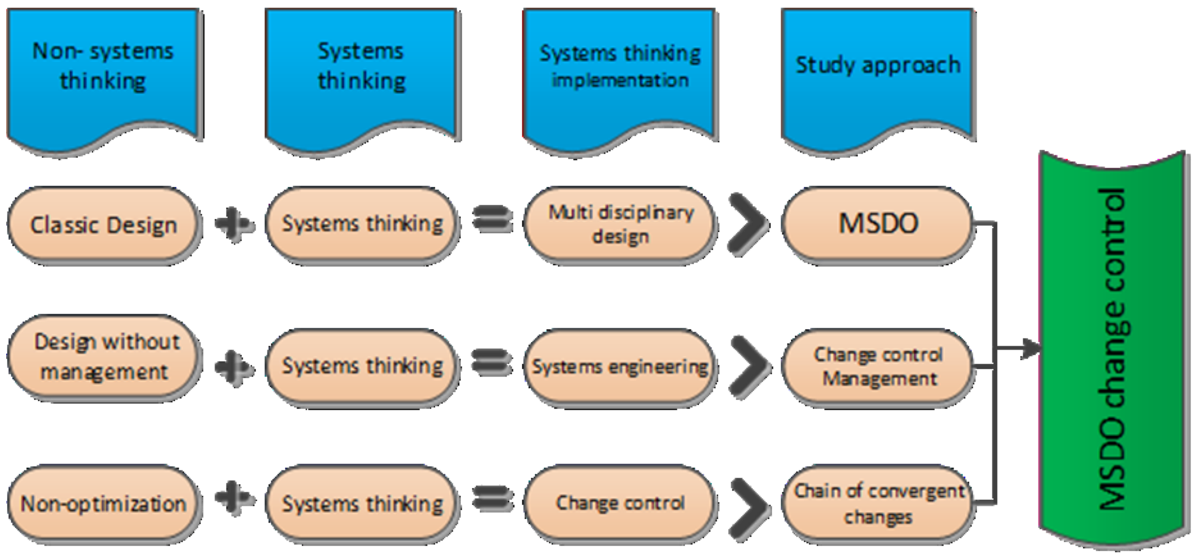

Figure 1. The Logic of this research

3.1. Matrix of component activities[1]

The DSM method (using structural design matrixes) is an information exchange model that allows the designer to determine the relationship between system parameters by data exchange (Eppinger and Browning, 2012). The probabilities and effects of changes between system components are stored in the DSM to determine and detect the variability of complex engineering systems (Clarkson et al., 2004; Koh et al., 2013). In this paper, two models of DSM matrixes are used in combination. Combining product and activity[2] matrixes and creating combined matrixes CA-DSM[3] that create sensitivity matrixes by combining activities and product elements. The reason for using a combined matrix is easier change control for complex products. The relationship between components in product DSM and activity DSM are explained. The matrix containing these two properties, called the Product Activity Design Structure Matrix (CA-DSM), is shown in Figure 2.

[1] CA-DSM
[2] Activities are derived from design process
[3] Components Activity- Design Structure Matrix

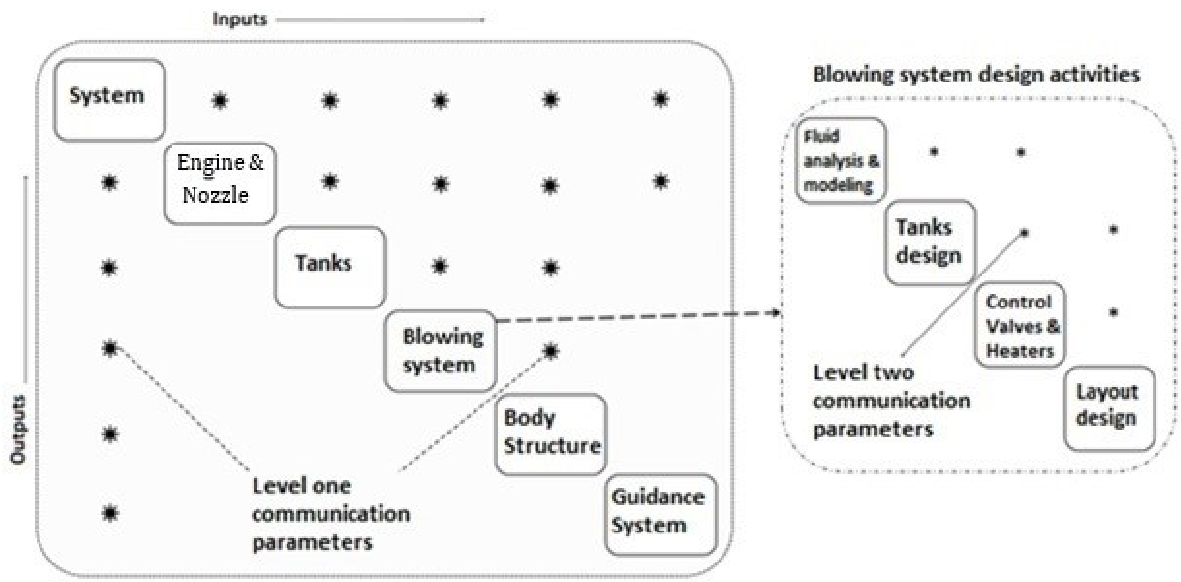

Figure 2. Product Activity Design Structure Matrix (CA-DSM) of Space Orbiter.

Level 1 parameters include the parameters relating to the subsystems or specific components in the large matrix diameter. Level 2 parameters include the parameters relating to the various activities within the small matrixes for each large matrix component. The design of each component in a subsystem can be the result of the work of several experts. However, a team or an individual activity is a parallel activity. For this reason, choosing such a matrix helps to accelerate and simplify relationships to control change.

In the CA-DSM matrix, these two properties are:

1. The main matrix contains the relationship of level 1 parameters, which uses the DSM logic of the product.
2. The matrix of each subdivision includes the relationship between the activities of that subsystem and the relationship between the level 2 parameters.

The strength of using the CA-DSM combined matrix is the ability to simultaneously switch between activities - work processes and product elements at the subsystem and system levels.

3.2. Design model

Each design phase (conceptual, preliminary, detailed) consists of several major sections (Hamraz, 2013; Plehn, 2018), including a set of system parameters. For example, design propagation levels can be defined in such a way that it first includes constraints on the main dimensions, then geometric constraints, then quantities, and finally tolerances (Masmoudi et al., 2017). The comprehensive design model using the Figure 2 matrix is shown in Figure 3:

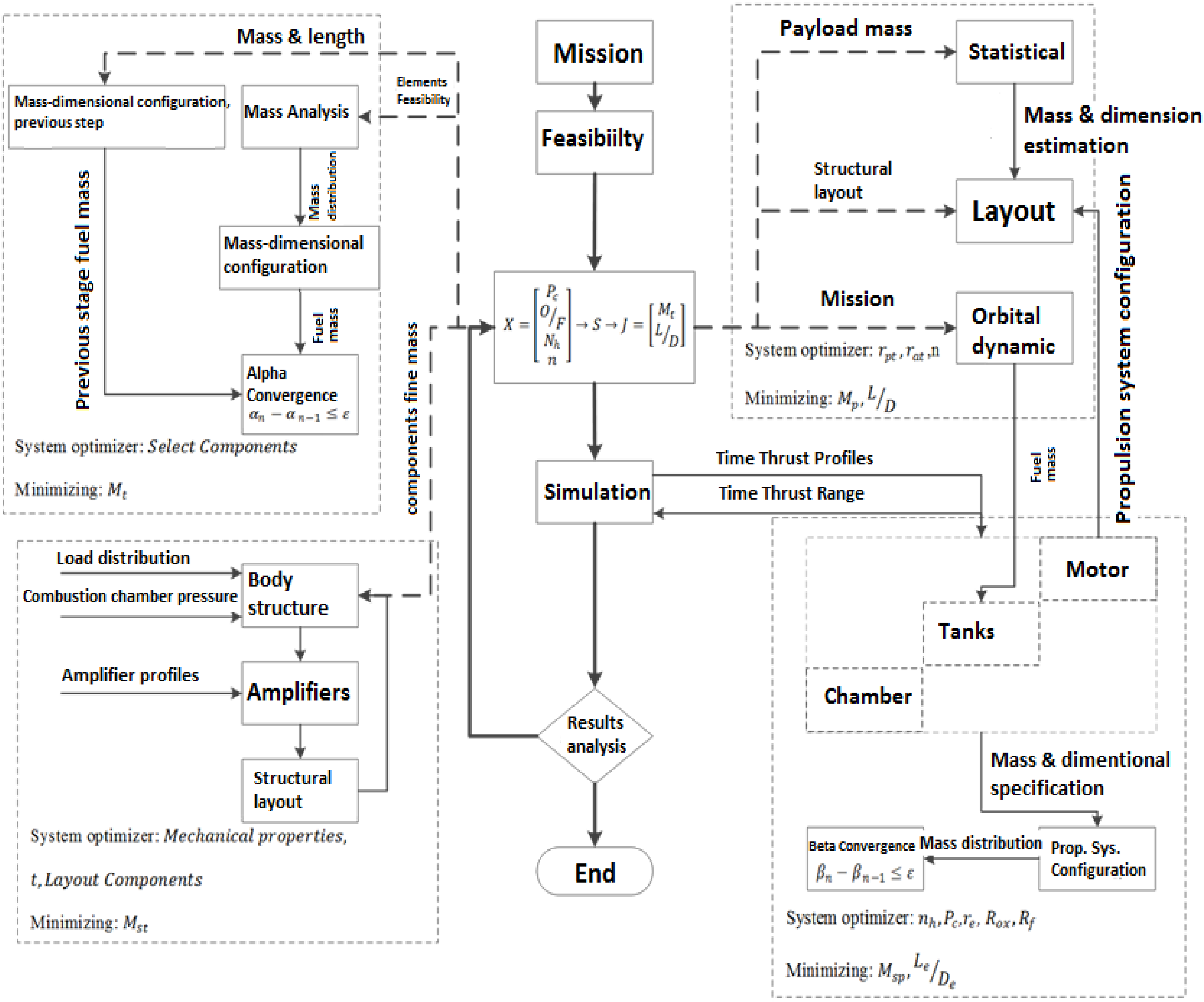

Figure 3. Design of space orbiter to implement change control in systems engineering processes.

3.3. Engineering change evaluation code[1]

Sensitivity of design changes should be developed in parallel with the design process (Li and Zhao, 2014). As the design process moves forward, so does the process of sensitizing change to affected activities. Failure to do so will lead to the closure of the change loop, ultimately leading to increased time and cost and even project failure.

A change in any of the Level 1 parameters can lead to a change in the other Level 1 parameters as well as the Level 2 parameters in proportion to the Level 1 parameters. At the same time, it is possible to develop code that converges all the requirements of the changes,

[1] CEC

considering the constraints. Of course, in developing this model, the work of the chief designer is difficult and requires a high level of knowledge. Without such knowledge, this model would be very time-consuming and costly. Figure (4) shows the CEC software algorithm:

The code consists of the following three parts:

- The first part of the sensitivity part: In this part, the sensitivity of all the parameters inside the matrix is done.
- The second part of the design: In complex systems, specific and limited relationships can be obtained for mass-dimensional configuration. In this section, the use of relations (system equations) for the relationship between level one parameters and system equations for subsystem design is for the relationship between subsystem parameters. In this section, the range of change of all system parameters due to the change of one parameter is calculated.
- The third part of the convergence part: In this part, the relationship between all level one and two parameters is converged in the design process, and the minimum changes of the parameters compared to the changed parameter are obtained. The most important output of the software is the designer achieving the results of the review of changes.
- Configuration management center review section: In this section, it achieves the desired results according to the algorithm in Figure 4.

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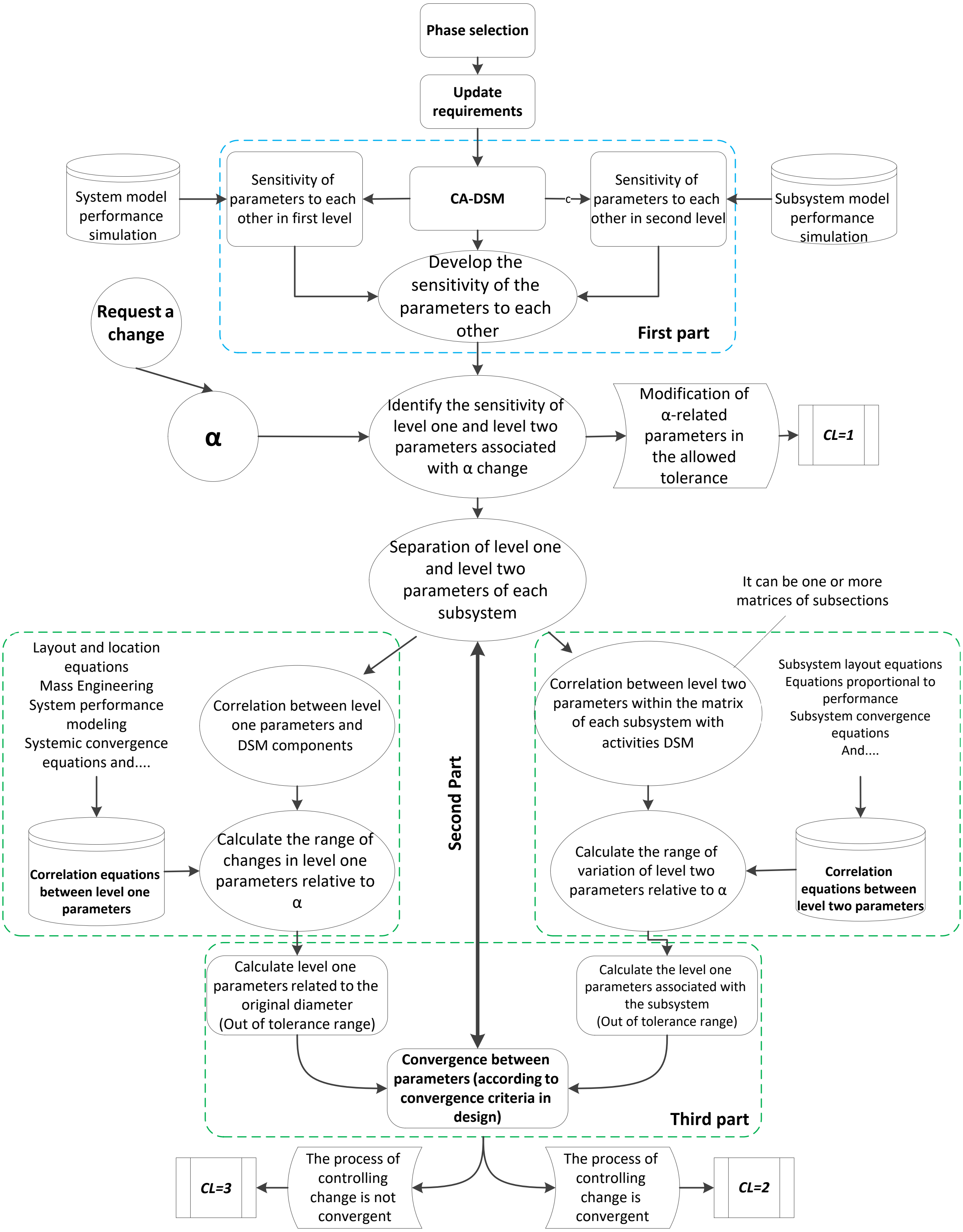

Figure 4. Evaluating Changes in the Design Process Algorithm

3.4. Engineering change transfer model

Finding the correct change propagation path for products with complex relationships is very difficult (Tang et al., 2016). It should be noted that the use of a linear and serial algorithm model, control and management of changes in projects with a variety of parameters, elements, relationships, and different environmental conditions, face serious problems, and it is necessary to develop a suitable algorithm. To eliminate this shortcoming (Hamraz et al., 2013). In these projects, methods and algorithms should be sought that have the necessary flexibility in the face of diverse and complex specialties and subsystems (Hamraz et al., 2013). In order to create a proper transfer path in complex systems, in addition to the need for the knowledge of the chief system designer, the knowledge of the chief designers of the subsystems and system tools is needed to create an integrated model of the change transfer algorithm. The algorithm for creating a transfer model for complex systems is shown in Figure 5.

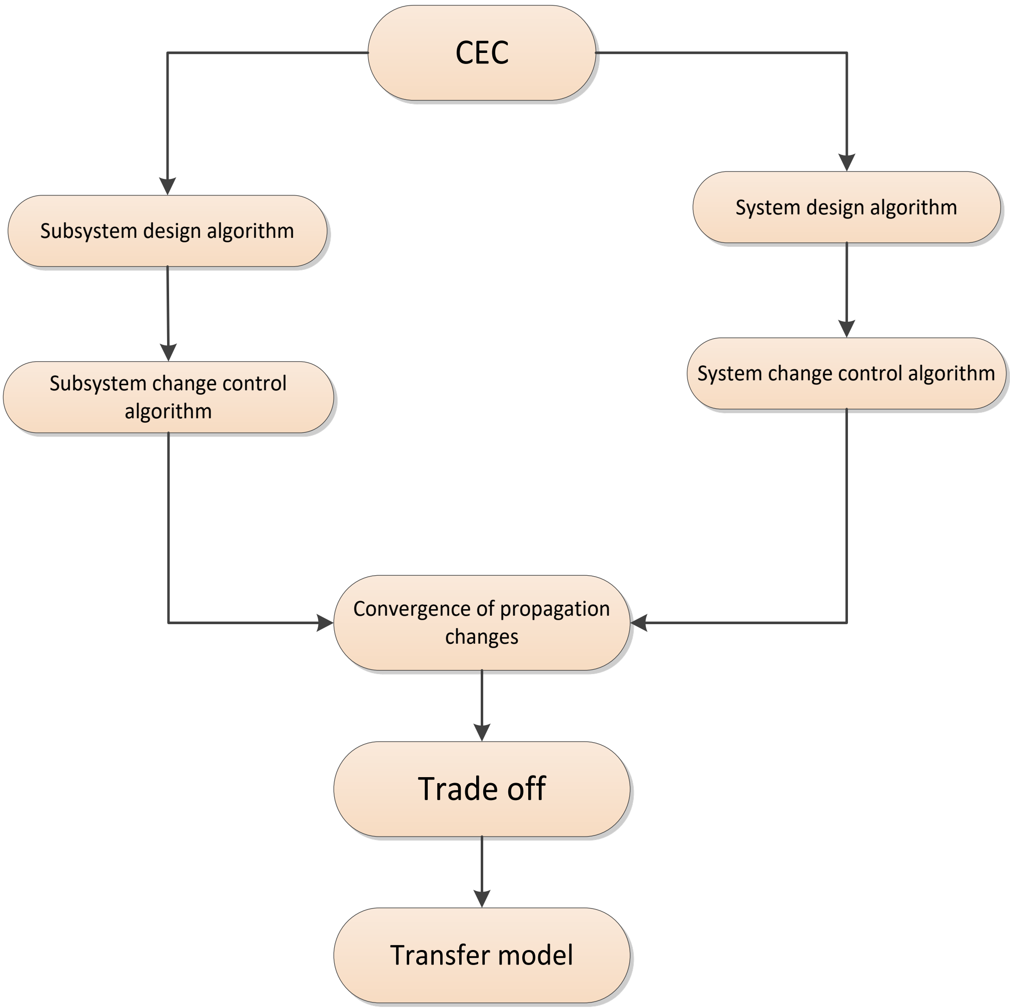

Figure 5. Transfer Model of Complex Systems

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According to the algorithm in Figure 5. the creation of the change control algorithm is obtained as a result of the expertise of the head designer and the use of the following:

- CEC software for the range of changes caused by the change
- Convergence algorithm designed to create seamless relationships between level one parameters
- CA-DSM matrix as a roadmap for all possible interactions paths between parameters

Also, the knowledge of controlling subsystem changes is obtained as a result of the expertise of subsystem designers and the use of the following:

- The DSM Activities matrix of each subsystem
- Convergence algorithm designed to create seamless relationships between level parameters of two subsystems
- Analysis of laboratory and engineering tests

Knowledge of change control at the system level and subsystems for each change request leads to a system change control algorithm. The trade-off of the possible paths by these algorithms together and convergence between information exchanges create the transfer model (Plehn, 2018; Acar et al., 2005).

3.5. Configuration management center

In the design phase, a present process for the amount of workload cannot be defined. Therefore, to define the cost, time, and workload of all changes, the configuration management canter needs to achieve different dimensions of the impact of a change in the product life cycle (Tang et al. 2016). The questions and the effect of each of the following should be specified for the configuration management center:

- ✓ Is this change to improve the requirements?
- ✓ Is this change due to design constraints such as lack of space or assembly problems?
- ✓ Is this change due to a low level of technology, lower cost, or inability to purchase some parts?
- ✓ Is this change due to other changes in the product?
- ✓ Is this a bottleneck, and should it be done?

The relations in Table 2 are used to qualify these questions.

Table 2. Comparison of different methods in control of engineering changes

How to produce	Symbol and impact number	Coefficient Name
Chief Designer	a (1..4)	Workload
project manager	b (1..4)	Consumer resources
Related parts	c (1..4)	Time
Simulation Chief Designer	$if \begin{array}{l} + \rightarrow\ d\ (0.25..1) \\ - \rightarrow\ d\ (1..4) \end{array}$	Improve requirements
project manager	$if \begin{array}{l} + \rightarrow f\ (0.1..1) \\ - \rightarrow f\ (1..2) \end{array}$	Throat

The following points are written to explain Table 2:

- ✓ The selection of value of the impact number is obtained qualitatively by the relevant people.
- ✓ Values greater than 1 indicate a greater impact intensity, and values less than 1 lead to positive effects of change.
- ✓ The head designer obtains the workload coefficient after using CEC.
- ✓ The project manager determines the coefficient of consumption resources after announcing the opinion of the involved parts.
- ✓ The time coefficient is determined after announcing the time required for each sub-section to perform its specific activity.
- ✓ The requirements improvement coefficient is obtained after reviewing the head designer or the person in charge of performance analysis (simulator) to influence the change in the improvement requirements according to the customer.
- ✓ The bottleneck coefficient is obtained due to the forced effect of a change to eliminate the bottleneck or the lack of suitable materials, parts, etc.

The probability value of the effect is obtained from the following equation:

$$PE^{1} = a \times b \times c \times d \times f \quad (1)$$
$$CT^{2} = b \times c \quad (2)$$

Depending on the effect parameter probability (PE) and time and cost (CT), a small change can be made to the managerial decision. PE quantifies the impact of the requested change on the project and quantified CT measures the amount of time and cost involved.

[1] Probability effect
[2] Cost and Time

4. Change control algorithm

A change request can be made by any of the subsystems. This request is made for one of the following reasons:

- Propagation of design failure structure
- Reduce costs
- Layout restrictions and space involved
- Improve customer requirements
- Optimization in design

In the first step, the change request is sent to the configuration management center, which reviews the change request according to the effects of the change. Tracking and execution of the change control management algorithm in Figure 6 are done by the configuration management center. This algorithm is performed according to the needs of the project manager, system head, and personnel working on the project. The comprehensive change control management algorithm consists of five main parts:

1. Configuration and sensitivity of all matrix parameters to each other
2. Limiting levels of each part of a design phase
3. Use of CEC software
4. Trade-off possible ways (transfer model)
5. Management evaluation in order to manage the life cycle

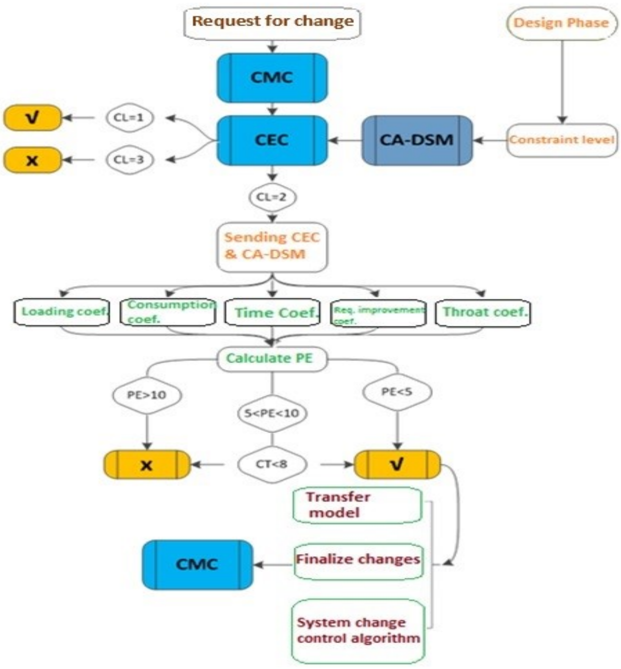

Figure 6. Comprehensive change control algorithm for large engineering projects

5. Results of a case study

The CA-DSM matrix is shown in Figure 2 for the orbital transmission block. The execution process for a new change request is given using this matrix.

Change request α: 10% increase in nozzle length due to proper accuracy in rotation of the nozzle according to the requirement of the operator connected to the nozzle (passing the system requirement)

According to the algorithm of Figure 6, after receiving the change request from the configuration management center, the above activities are performed in order:

1. Compilation of CA-DSM matrix (Figure 1)
   - ✓ Design phase: preliminary design
   - ✓ Leveling: Total dimensional parameters
2. Use the CEC program to assess the sensitivity of the effects of change and identify the system parameters involved
   - Part 1 of CEC: Development of sensitivity of all parameters to each other by functional simulation of subsystems, which is available as an example in references (Nosratollahi et al., 2015a) and (Ali Mohammadi et al., 2013).
   - Part II CEC: Calculating the range of changes in level one parameters relative to the change in α and calculating the range of changes in level two parameters relative to the change in α in the subsystem algorithms (Nosratollahi et al., 2015) and (Nosratollahi et al., 2016).
   - Part III CEC: Convergence of changes in the design process using the β convergence coefficient criterion (Nosratollahi et al., 2016).

$$\beta = \frac{dry\ mass}{dry\ mass + fuel\ mass} \tag{3}$$

Preliminary result of using CEC software to change α, value CL = 2

3. Send CEC information and CA-DSM sensitivity by the configuration management center to the relevant parts.
4. Calculation of configuration management coefficients according to Table 3:

Table 3. configuration management coefficients

Coefficient name	Quality level	Quantification
Workload (total activities + complexity of matrix interactions)	Subset level = 1 Subsystem level = 2 System convergence level = 3 System heterogeneous level = 4	a=3
Resources (added time + cost to the project)	Less than 0.1% = 1 Less than 1% = 2 Less than 5% = 3 More than 5% = 4	b=2
Time involved parts (change in project Gantt time)	No change = 1 Less than 0.1% = 2 Less than 5% = 3 More than 5% = 4	c=2
Improve requirements	No effect = 1 Positive effect = less than 1 Low negative impact = 2 High negative impact = 3 Large change in a main requirement = 4	d=0.8
Throat	Removable in the range of resources = less than 1 Irresistible in the range of resources = more than 1	f=1

5. Calculate the probability values of the effect and the effect of time and cost:

The value is PE = 6.4 and CT = 4, and the change is confirmed by CMC.

6. The system change control algorithm is obtained according to the model of Figure 6 according to Figure 7. This algorithm is a significant process to avoid a chain of multiple and divergent changes.

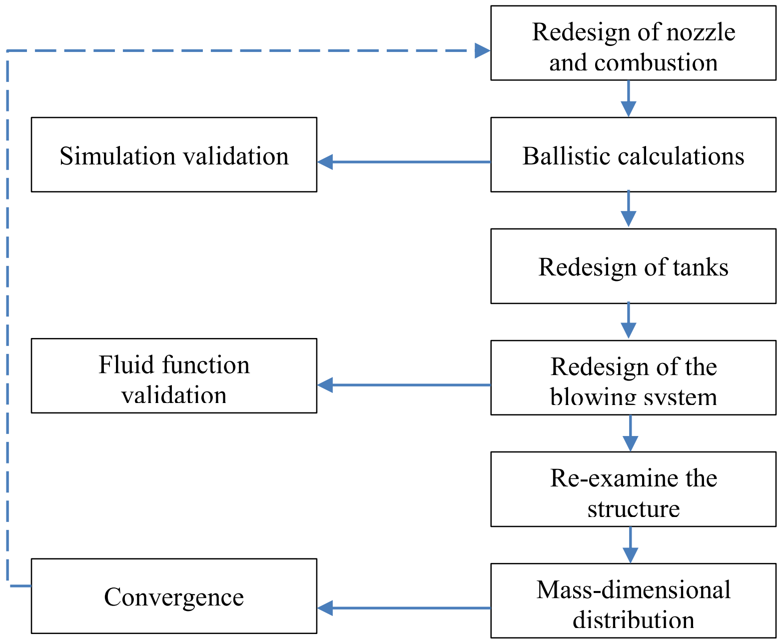

Figure 7. Systemic Change Control Algorithm for α Requested

7. Transfer model: Using the algorithm of Figure (7) and CEC software, the best transfer method is obtained according to Figure (8).

This model is the result of the Trade-off process of the parameter cycle in the design convergence cycle with the criterion of the minimum chain of changes.

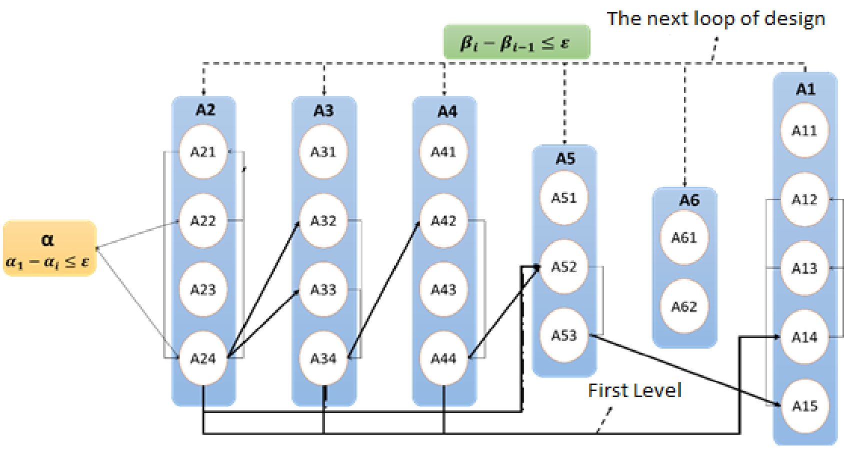

Figure 8. Transfer Model for α Requested

In this figure, A1 = system, A2 = motor, nozzle and chamber, A3 = tanks, A4 = blowing system, A5 = internal structure and body, and A6 = guidance system, and also Aij = sub- are activities related to each subsystem.

Control of changes of a 10% increase in nozzle length demand ultimately results in a 2% effect of dimensional change in the propulsion subsystem, a 5% effect of oxidation tank dimensional change, and a 3% effect of oxidation tank dimensional change. Also, other changes have changed in the form of subsequent changes following the chain of changes.

Table 4. Change system parameters

Rows	System requirement	Before change	After change
1	Convergence coefficient	0.1249	0.1251
2	The final crime	3.391 ton	3.397
3	Total crime	16.64 ton	16.648
4	Nozzle expansion ratio	38.75	39.9
5	Engine length	2.04 m	2.0818
6	Number of blow tanks	6	7
7	The radius of the tail tanks	257.2 mm	244.31
8	Fuel tank height	0.72 m	0.69
9	Fuel tank radius	1.18 m	1.19
10	Oxide tank height	1.18 m	1.16
11	Oxide tank radius	1.18 m	1.19

The process of changing the system parameters from the initial state to the post-change state is shown in Table 3. It should be noted that eleven change requests from the configuration

management center (CMC) could have led to design divergence, and by using the current modern method based on system thinking, the best suggestions for changes in the optimization loops were extracted in such a way that the design is also converged.

6. Conclusion

Aerospace products have complex relationships in design processes. For this reason, the systematic design process of these products requires the development of appropriate and usable configuration management. The change control process is also one of the main activities in the propagation and development of product design. If you do not use a system logic, controlling any changes can complicate the design process and confuse project designers. Therefore, in order not to increase the time and high cost in the project design process and create a system logic to control change, an efficient and new approach was presented in this paper. This approach has been developed using systems engineering theory to improve design processes.

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